Advanced Numerical Methods for NWP Models

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LONG-TERM GOAL

The long-term goal of this research is to construct the Navy's next-generation global numerical weather prediction (NWP) model using new numerical methods specifically designed for distributed-memory computers. To take full advantage of the new computer architectures, the spherical global domain must be partitioned into local sub-domains, or elements, which can then be solved independently on the multiple processors of these computers. The numerical methods used on these sub-domains must be not only local in nature but also high-order in accuracy and highly efficient. Thus the final objective of this project is to construct a new global NWP model which is as accurate as the current spectral model Navy Operational Global Atmospheric Prediction Systems (NOGAPS) while much more efficient, thereby allowing for finer resolution forecasts.

OBJECTIVES

The objective of this project is to construct high-order local methods for the Navy's next-generation global NWP model. The high-order accuracy of these methods will ensure that the new model yields the same accuracy as the current spectral model while the locality of these methods will ensure that the efficiency of the model increases.

APPROACH

To meet our objectives we explore:
1. spectral element (SE) methods,
2. spectral elements in space with semi-implicit and semi-Lagrangian methods in time, (SESL)
3. vertical mode decomposition to reduce the Helmholtz equation from 3 to 2 dimensions,
4. fast matrix solvers on distributed-memory computers.

The power of spectral element methods is that they are high-order accurate, like spectral transform methods (i.e., spherical harmonics), yet are completely local in nature – meaning that the equations are solved independently within each individual element and processor. Semi-Lagrangian methods are also being considered because these methods, like high-order methods, have minimal dispersion errors. This property is important for properly capturing fine-scale atmospheric phenomena (e.g., tropical cyclones). In addition, semi-implicit and semi-Lagrangian methods offer vast improvements in efficiency due to the longer time steps that they permit.

After validation of the spectral element, semi-implicit, and semi-Lagrangian discretization on barotropic test cases, the vertical integration scheme for the full 3D primitive equations needs to be scrutinized. The semi-implicit time-integration scheme of the 3D primitive equation model, which we

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call the NRL spectral element atmospheric model (NSEAM), must then be ported to the message-passing interface (MPI). At this point direct comparisons with the current version of NOGAPS must be made. Superior performance of NSEAM over NOGAPS would then justify the further effort to make NSEAM the operational next-generation NWP model. To accomplish the final objective, the NSEAM dynamical core needs to be coupled with the physical parameterization package already in existence within NOGAPS.

WORK COMPLETED

The SE and SESL discretization methods were tested on the spherical shallow water equations. These methods have been tested extensively and two papers have been written concerning these innovative approaches (Ref. [1,2]). The 3D model, NSEAM, has undergone extensive validation and performance testing. Four test cases have been applied to NSEAM and this work was presented at a conference in Garching Germany (Ref. [4]) and at an invited talk at the Max-Planck Institute in Hamburg Germany (March 2003). The parallel version of the semi-implicit time-discretization of NSEAM has been completed. The comparison of NSEAM to NOGAPS can be summarized as follows: NSEAM yields the same exponential accuracy as NOGAPS while being at least 50% faster (at T239 L30 resolution). At the next projected operational resolution of T479 L60, a conservative estimate shows that NSEAM will be anywhere from 100% to 200% faster than NOGAPS. The impressive performance of NSEAM is due to the fast GMRES iterative solver used to solve the Helmholtz operator resulting from the semi-implicit time-discretization. In addition, instead of solving a full 3D Helmholtz operator, the equations are decoupled into a series of 2D Helmholtz operators via vertical mode decomposition. Since only the fastest three modes need to be solved, then the cost of the semi-implicit is only three 2D Helmholtz operators, which is equivalent to solving three shallow water models.

RESULTS

Horizontal Operators. To show the accuracy of the SE method that is used to discretize the horizontal operators in NSEAM, in Fig. 1 we show results for nonlinear zonal geostrophic flow (barotropic Case 2 in Ref. [3]). Note the high-order spectral accuracy achieved by NSEAM.
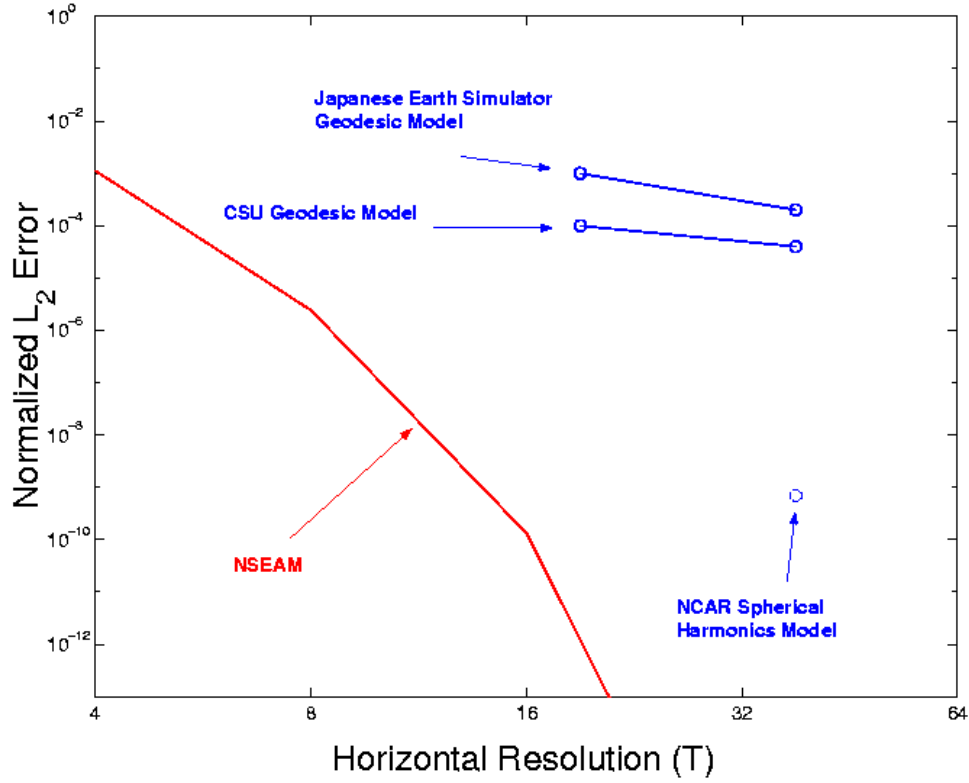
Figure 1: L2 error as a function of horizontal resolution for the NRL's spectral element atmospheric model (NSEAM), Japanese earth simulator finite volume, CSU finite volume code, and the NCAR spherical harmonics model.

NSEAM is more accurate than the other three models: two finite volume models and a spectral transform model. In Ref. [3] we show that NSEAM is indeed more accurate than all currently existing models. A similar result is obtained with SESL (Ref. [2]) while using time-steps 10 times larger.

3D Model. As a first test to validate the 3D, model a Rossby-Haurwitz wave number 4 was run both with NSEAM and NOGAPS. This test simulated a 5-day forecast using a resolution of T80L24 and the results show that both models yield identical results (see Ref. [3] and ONR 2002 report).
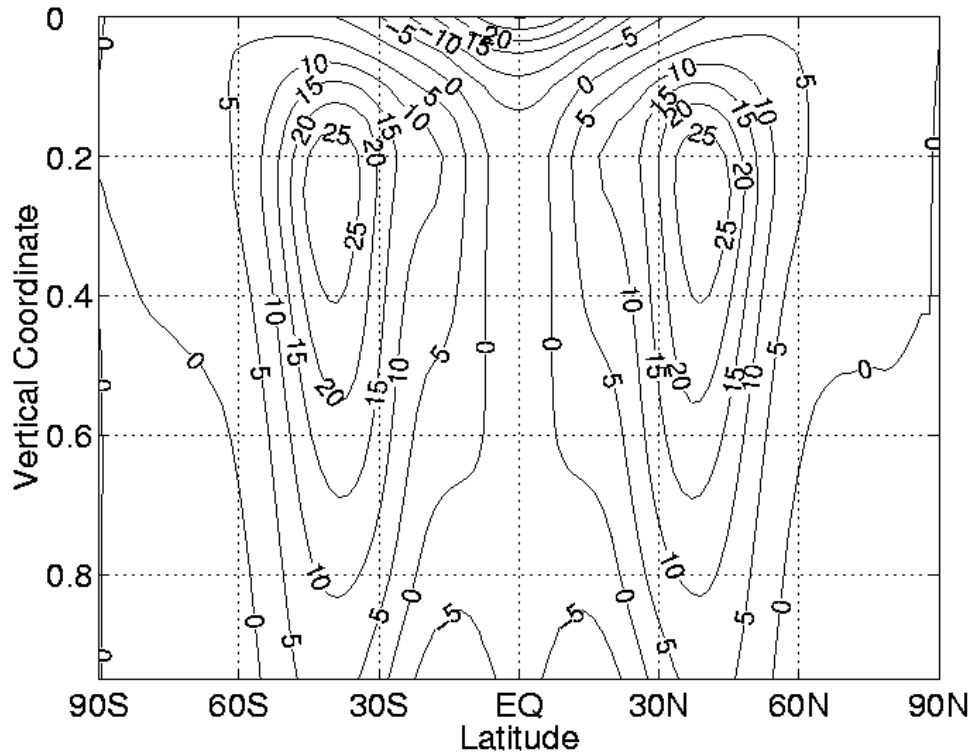
Figure 2: Zonally-averaged zonal velocity (U) for the NRL spectral element atmospheric model (NSEAM) running the Held-Suarez test case with T64 L20 as a function of latitude and vertical coordinate for a 1200-day integration.

As a second test, NSEAM was run with the Held-Suarez test case. This case is the primary test for all new atmospheric models because it mimics a realistic atmosphere with physical parameterization. Figure 2 shows the contour plot of the mean zonally averaged zonal velocity as a function of latitude and vertical coordinate for T64 L20 for a 1200-day integration. Figure 2 compares well with the results of Held-Suarez and those from the European Center for Medium-Range Weather Forecasting (ECMWF) spectral transform model and clearly shows the formation of the jet stream (in the mid-latitudes). In addition, the model is stable for long time-integrations.

As a third test, baroclinic instability was studied. This case is a two-part test: in the first part, a 30-day simulation is executed to ensure that the model maintains the initially balanced state. The second part involves adding a perturbation to the initial state and then tracing the evolution of the baroclinic instability. NSEAM was able to maintain this balanced state for 30 days and beyond thereby confirming that the model generates no spurious waves. This test is of interest because other geodesic grid models have yet to remain stable due to unphysical number 5 waves generated by the grid in conjunction with the low-order methods. This test clearly shows the need for high-order numerics in atmospheric models when unstructured irregular grids are used. In Fig. 3 we plot the minimum surface pressure for the baroclinic instability for NSEAM and three well-established models. They are: the icosahedral model of the German Weather Service (GME), the Lin-Rood NASA flux-form semi-Lagrangian model (NASA), and the National Center for Atmospheric Research (NCAR) spectral transform model. The two dotted lines (GME and NASA) are both low-order models while the two solid lines (NSEAM and NCAR) represent high-order models. Note that the two low-order models

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behave similarly while the two high-order behave similarly to each other. This test shows that while NSEAM is a grid point model it does behave like a spectral transform model and this behaviour is directly due to the high-order numerics that it uses.
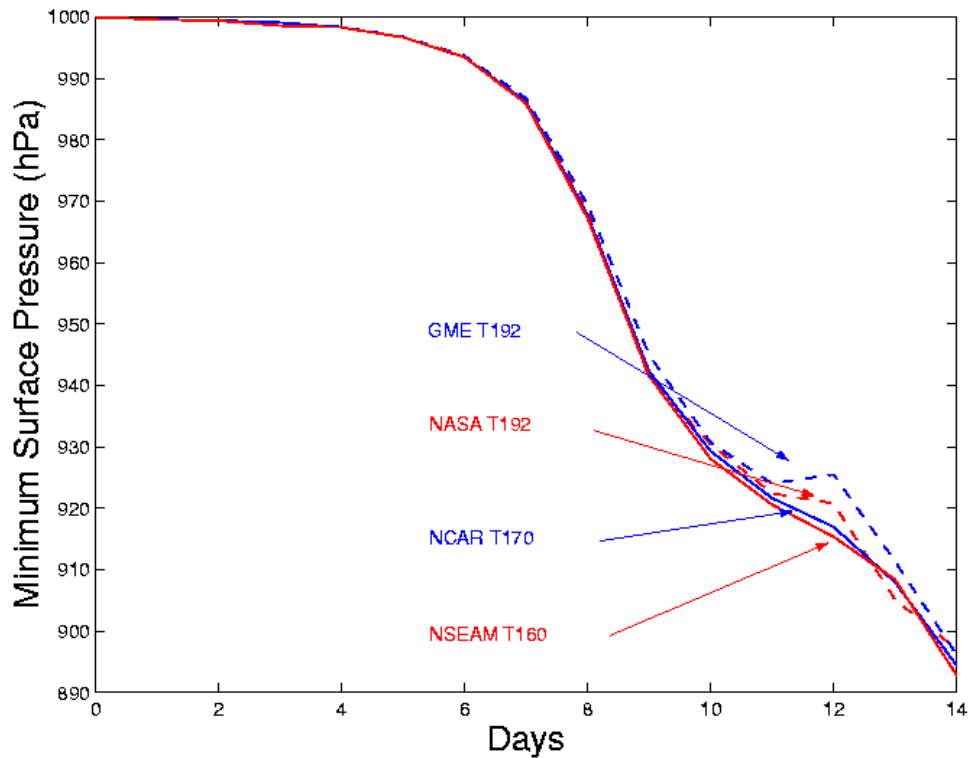

Figure3: The minimum surface pressure as a function of days for the NRL's spectral element atmospheric model (NSEAM), the German Weather Service icosahedral model (GME), the NASA flux-form semi-Lagrangian model (NASA), and the NCAR spectral transform model (NCAR).

Finally, to show the scalability of the Navy's next-generation model, in Fig. 4 we compare NSEAM with NOGAPS using the maximum time-step that each model can use with the operational resolution T239 L30. No physical parameterization is used in this comparison; only the dynamical cores of the models are used.

This result clearly shows that NSEAM can use far more processors than NOGAPS and it also scales better than NOGAPS. At this spatial resolution NSEAM can easily use 20,000 processors while NOGAPS can only accommodate 240 processors efficiently. Very few models will be able to scale at the rate of NSEAM.

IMPACT

NOGAPS is run operationally by the Fleet Numerical Meterology and Oceanography Center (FNMOC) and is the heart of the Navy's operational support to nearly all DOD users worldwide. This work targets the next-generation of this system for massively parallel computer architectures. NSEAM has been designed specifically for these types of computer architectures while yielding the same high-order accuracy as NOGAPS.

TRANSITIONS

Improved algorithms for model processes will be transitioned to 6.4 (PE 0603207N) as they are ready, and will ultimately be transitioned to FNMOC with future NOGAPS upgrades.
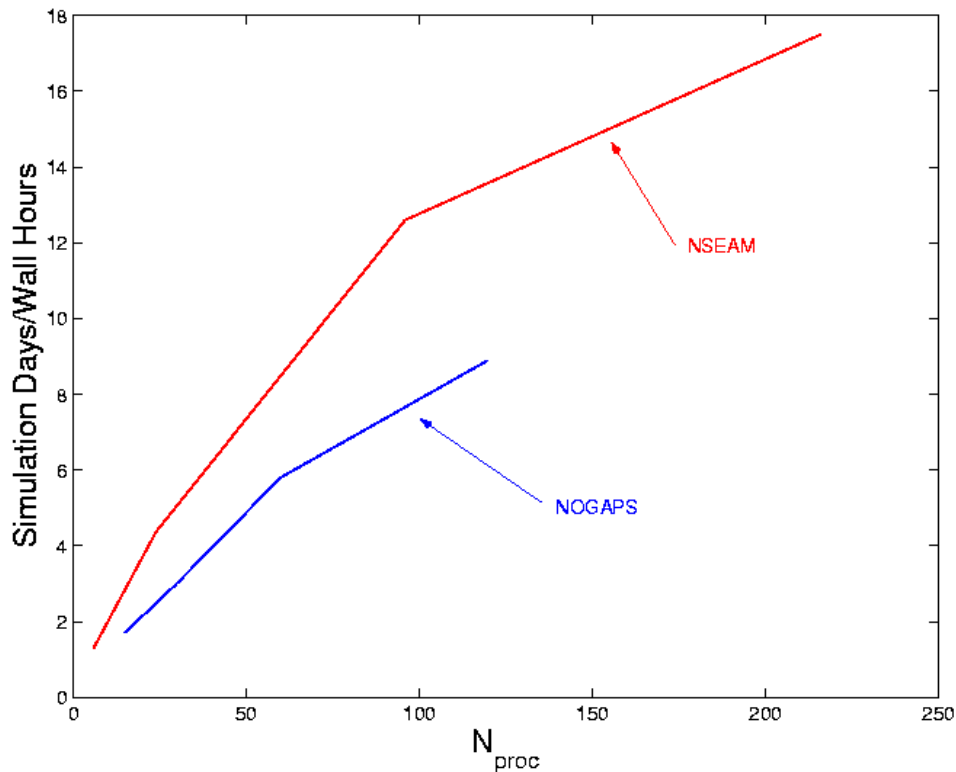

Figure 4: Scalability of the NRL's spectral element atmospheric model (NSEAM) compared to NOGAPS for the operational resolution T239L30 on an IBM SP4. The number of simulation days per wall clock hours is given as a function of processor number.

RELATED PROJECTS

Some of the technology developed for this project will be used immediately to improve the current spectral transform formulation of NOGAPS (NRL BE-35-2-18).

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